

Simulation of the December 1998 Stratospheric Major Warming

G. L. Manney,¹ W. A. Lahoz,² R. Swinbank,³ A. O'Neill,² P. M. Connell,⁴ R. W. Zurek¹

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¹Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA

²Centre for Global Atmospheric Modelling, Reading, UK

³USRA, NASA Goddard Space Flight Center, Greenbelt, MD

⁴United Kingdom Meteorological Office, Bracknell, UK

Abstract. An atypically early major stratospheric sudden warming in mid-Dec 1998 resulted in an abnormally warm and weak polar vortex through most of the 1998-99 winter. The first major warming in nearly 8 years, it was only the second major warming observed before the end of Dec, and strongly resembled the previous Dec 1987 major warming. 3D Mechanistic model simulations reproduced all of the main features of the unusual Dec 1998 major warming, including the magnitudes of zonal mean easterlies and temperature increases, and the 3D evolution of the flow.

Introduction

Prior to 1991, major warmings (defined by increasing zonal mean temperatures and zonal mean easterly winds from 60°N to the pole at 10 hPa) typically occurred approximately once every two Arctic winters; a major warming in mid-Dec 1998 was the first since Feb 1991 [e.g., *Pawson and Nanjokat*, 1999, and references therein]. The Dec 1998 warming was also the second earliest on record. The earliest, and the only other major warming on record before the end of Dec, was in early Dec 1987; prior to that, the earliest was in late Dec/early Jan 1984-85 [*Baldwin and Dunkerton*, 1989]. The 1984-85 and 1987 warmings resulted in the warmest and weakest lower stratospheric polar vortices in the 20 years before 1998-99 [*Zurek et al.*, 1996]. Fig. 1 compares temperatures and vortex strength in 1998-99 with those in the previous 20 years, using the US National Center for Environmental Prediction (NCEP) record; 1987-88 and 1984-85 are also highlighted. The Dec 1998 warming had a more pronounced effect on mid-stratospheric temperatures than the Dec 1987 warming (Fig. 1a), although smaller than that of warmings later in winter (e.g., 1984-85). 10-hPa temperatures fell well below average again in late Jan 1999 and remained unusually low until an early final warming began in late Feb. 840 K PV gradients (Fig. 1c) set a record minimum in Jan 1999, but were near average in Feb before the final warming. The effect of the Dec 1998 warming on lower stratospheric temperatures was comparable to that of other major warmings; there was a brief period of record-high minimum 46-hPa temperatures in early Jan 1999 (Fig. 1b), and temperatures then fell to near average for a short period in mid-Feb. Lower stratospheric PV gradients were the weakest on record during the 1998-99 winter (Fig. 1d). The evolution of the vortex and minimum temperatures during 1998-99 was remarkably similar to that during 1987-88, the only previous year when a major warming was observed before the end of Dec.

A 3D, primitive-equation model with lower boundary forcing from observations in the lower stratosphere was used to simulate the Dec 1998 major stratospheric warming. We present here a description of the Dec 1998 warming and initial comparisons of the simulations with data. The successful simulation of the unusual early major warming in Dec 1998 will

facilitate future more detailed studies of dynamics and transport during this event.

Data, Analysis, and Model

UK Meteorological Office (UKMO) data [Swinbank and O'Neill, 1994] were used for initialization, boundary forcing, and comparison with model results in the simulation we focus on here. A problem with assimilation of satellite data in fall 1998 led to erroneously low upper stratospheric UKMO temperatures. This problem was corrected on 2 Dec 1998; UKMO upper stratospheric temperatures for several days thereafter may still have a small cold bias. To examine sensitivity to details of initialization and boundary fields, simulations were also done using NCEP analyses (with winds calculated from the geopotential heights) for initialization, one using the NCEP data for lower boundary forcing as well, and the other using the UKMO data for boundary forcing. The sPV shown here was calculated from UKMO winds and temperatures and scaled in "vorticity units" [e.g., Baldwin and Dunkerton, 1989; Manney *et al.*, 1994a].

The UK Universities Global Atmospheric Modelling Project (UGAMP) Stratosphere-Mesosphere model (USMM) [Thuburn and Brugge, 1994], configured as described by Mote *et al.* [1998], was used to simulate the warming. A T42 truncation ($\sim 3^\circ \times 3^\circ$ horizontal resolution) was used with 34 levels in the vertical (~ 1.6 km vertical resolution) and a lower boundary at 100 hPa. The USMM was run with online transport calculations [Thuburn and Brugge, 1994]. Model PV was calculated with a different algorithm than that used for the UKMO and NCEP data. The model was initialized on 5 Dec 1998, with daily geopotential heights from UKMO or NCEP as the lower boundary forcing.

Results

At 10 hPa, zonal mean easterlies first appeared at 60°N on 15 Dec in the UKMO data, ~ 1 d after the temperature gradient north of 60° changed sign (Fig. 2a,c). Both events

occurred ~ 2 -d earlier in the USMM run using UKMO initialization and lower boundary forcing (Fig. 2b,d). Both USMM and UKMO data show easterlies developing at 60°N ~ 4 d earlier at 1 hPa than at 22 hPa (Fig. 2e,f). The agreement between UKMO and USMM 60°N zonal mean temperatures is good throughout the period (Fig. 2g,h). 10 hPa temperatures increased by ~ 45 K at 84°N and easterlies over 25 m/s appeared in both USMM and UKMO data. The modeled high-latitude winds and temperatures take ~ 5 d longer to recover; the evolution at lower latitudes and the progression of the recovery everywhere after ~ 30 Dec agree well between model and data. In the USMM runs initialized with NCEP data, the secondary peak prior to the main warming in 10-hPa high-latitude temperatures (Fig. 2d) is absent, as is the high latitude secondary peak in easterlies on ~ 23 Dec (Fig. 2b); 10-hPa high latitude westerlies and low temperatures reappear ~ 2 d earlier than in the UKMO-driven run.

The zonal mean changes shown above were accompanied by strong wave amplification in the mid- to upper-stratosphere; this was associated with wave 1 amplification in 100-hPa geopotential heights in early to mid-Dec. Like the Dec 1987 major warming [Baldwin and Dunkerton, 1989], the Dec 1998 warming seems to be closely linked to wave 1 amplification in the upper troposphere. A UKMO-driven USMM run with only the zonal mean and wave 1 in the lower boundary forcing produced a major warming much like that shown in Fig. 2, confirming a close coupling to wave 1 in the boundary field.

For ~ 2 weeks prior to the intensification of the warming, the mid-stratospheric vortex was shifted off the pole in a pattern like that during a “Canadian” warming [e.g., Juckes and C’Neill, 1988], and similar to the “precursor” event to the Dec 1987 major warming [Baldwin and Dunkerton, 1989] – a large vortex shifted toward 0°E longitude with tongues of material drawn off its edge around the anticyclone, and a region of high temperatures drawn into high latitudes near 120° - 180°E . By 12 Dec (Fig. 3a), the anticyclone was intensifying, and the high temperature center shifted slightly northeast, to near 150°E , 60°N .

The anticyclone continued to intensify, and by 16 Dec (Fig. 3b) covered a large area including the pole with the vortex describing a narrow crescent south of 60°N . The USMM

vortex stretched $\sim 30^\circ$ further east compared to that in the UKMO data, and curved to lower latitudes at its western end; USMM temperatures were slightly lower, but positioned similarly. By 19 Dec (Fig. 3c), the anticyclone and high temperatures were centered over the pole; the vortex remnant was stretched around the anticyclone at $40\text{--}50^\circ\text{N}$. Unlike many “wave 1” warmings later in winter [e.g., *O'Neill et al.*, 1994], there was no sign of merging anticyclones – a single large anticyclone pushed the weakened vortex out to midlatitudes. The USMM shows a stronger and considerably larger vortex remnant near 90°E , but even higher temperatures over the pole. The run with NCEP initialization and boundary forcing showed a stronger vortex remnant than the data near 270° east and lower temperatures over the pole; the run with NCEP initialization and UKMO boundary forcing showing slightly stronger (compared to the UKMO data), but not larger, remnants near both 90° and 270°E , and polar temperatures very near those in the data.

By 23 Dec 1998 (Fig. 3d), both UKMO and USMM polar vortices were in fragments. The USMM vortex fragments remained farther off the pole, and temperatures higher over the pole, for several days in each of the runs, resulting in more prolonged zonal mean wind and temperature gradient reversals (e.g., Fig. 2). By 31 Dec, the observed vortex fragments rejoined near the pole, and the modeled vortex fragments were in the process of doing so. By 8 Jan (Fig. 3e), there was again a vortex/Aleutian high pattern with lower temperatures over the pole, but the vortex was much smaller and weaker than before the warming. The NCEP-initialized runs both had a morphology somewhat closer to the data on 8 Jan, but the run with NCEP boundary forcing had a weaker vortex. By 14 Jan, all USMM runs had morphology very similar to the data.

In the lower stratosphere (Fig. 4), the effects of the warming appeared later, with significant disruption of the vortex beginning around 23 Dec (Fig. 4b) and strong disruption continuing through mid-Jan (e.g., Fig. 4c). Temperature gradients in the lower stratosphere became very weak, and a significant region of low polar temperatures did not reappear until after mid-Jan. The USMM vortex remained slightly stronger than that in the UKMO data; all

USMM runs were very similar in the lower stratosphere.

In the upper stratosphere, the anticyclone was centered near the pole on 16 Dec (Fig. 5a), with highest (lowest) temperatures near 50°N , 60°E (60°N , 270°E). The vortex recovered quickly, reforming over the pole by 25 Dec. By 31 Dec (Fig. 5b), the vortex was strong, symmetric, and pole-centered. The USMM upper stratospheric vortex became weaker than that in the UKMO data (Fig. 5b), but by 8 Jan was again slightly stronger than in the data. The upper stratospheric vortex in the NCEP-initialized USMM runs remained too strong throughout the warming and high temperatures were centered $\sim 60^{\circ}$ west of those in the data around 16 Dec.

Comparison of Figs. 4a, 3b, and 5a shows a strong westward tilt of the vortex with height. Before the warming, there was $\sim 180^{\circ}$ westward tilt of the vortex over the depth of the stratosphere (Fig. 6a). After ~ 16 Dec (Fig. 6b), the westward tilt diminished; by 25 Dec (Fig. 6c) the vortex was nearly vertical and remained so until mid-Jan. A strong westward tilt prior to major warmings, decreasing after the peak, has been previously reported [e.g., Baldwin and Dunkerton, 1989; Manney *et al.*, 1994b, and references therein]. The cross-sections in Fig. 6 are sensitive to slight differences in vortex position, thus emphasizing differences between the USMM and the UKMO data. Fig. 7 shows the 3D vortex structure on 16 Dec. To emphasize the overall similarity, and because of small biases between UKMO and USMM sPV, we use different sPV contours for the USMM and UKMO isosurfaces. Fig. 7 shows that the model captures the overall 3D structure of the vortex and the degree to which the vortex was disrupted during the warming. At the peak of the warming (Figs. 6b, 7), the mid-stratospheric vortex was stretched out south of 60°N around the pole-centered anticyclone (Figs. 3c,d); the two ends of this connect with more localized vortices in the lower and upper stratosphere at $\sim 120^{\circ}\text{E}$ (Fig. 4a) and $\sim 300^{\circ}\text{E}$ (Fig. 5a). Remarkably similar 3D vortex structure was seen during the Dec 1987 major warming [Baldwin and Dunkerton, 1989]. Despite differences in the details of synoptic structure, the overall structure of the vortex shown in Fig. 7 was very similar in the NCEP-driven runs.

Summary and Conclusions

The first major stratospheric sudden warming in nearly 8 years, in mid-Dec 1998, resulted in an unusually warm and weak mid-stratospheric vortex during Jan 1999, and the weakest lower stratospheric vortex in the 20-year NCEP record for the rest of the 1998-99 winter. The vortex evolution during the Dec 1998 warming, and during the entire 1998-99 winter, bore a strong resemblance to that during 1987-88, the only other year on record with a major warming before the end of Dec. 3D mechanistic model simulations of the Dec 1998 major warming reproduced the overall evolution of the stratospheric flow, including peak 10-hPa zonal mean easterlies of ~ 25 m/s and 10-hPa zonal mean temperature increases of ~ 45 K. Although the modeled mid-stratospheric vortex remained somewhat too strong, and there were differences in detail between model runs, the main features of the 3D synoptic evolution of the vortex were reproduced in each simulation. These simulations will be used for further, more detailed studies of the unusual Dec 1998 major warming, and its effects on transport.

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W. A. Lahoz, A. O'Neill, CGAM, University of Reading, Reading RG6 6BB UK

P. M. Connew, UK Meteorological Office, Bracknell RG12 2SZ UK

G. L. Manney (M/S 183-701, e-mail: manney@mls.jpl.nasa.gov), R. W. Zurek (M/S 183-335), Jet Propulsion Laboratory, Pasadena, CA 91109

R. Swinbank, USRA, Code 910.3, NASA GSFC, Greenbelt, MD 20771

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Figure Captions

Figure 1. Minimum NCEP temperatures (K) north of 40°N at (a) 10 hPa and (b) 46 hPa; maximum sPV gradients with respect to equivalent latitude ($10^{-6}[\text{deg s}]^{-1}$) [Manney *et al.*, 1994a] at (c) 840 K and (d) 465 K. Shading shows the envelope for 1978-79 to 1997-98, thin white line the average for those years. Thin green and blue lines show 1984-85 and 1987-88, respectively; thick black line shows 1998-99.

Figure 2. Time-series of zonal mean winds (a, b, e, f) and temperatures (c, d, g, h) as a function of latitude at 10 hPa (a-d) and as a function of pressure at 60°N (e-h), from (left) UKMO data and (right) the USMM run with UKMO initial and lower boundary fields. -5 to 0 m/s is shaded in a, b; -10 to 0 m/s in e, f. 212 to 215 K is lightly shaded, and 236 to 239 K darkly shaded, in c, d; 215 to 218 K is lightly shaded, and 242 to 245 K darkly shaded, in g, h.

Figure 3. 840 K sPV (10^{-4} s^{-1}) maps from UKMO (left) and USMM (right). Temperature contours from 200 to 260 (by 10) K are overlaid in white. The projection is orthographic, with 0°E at the bottom and 90°E to the right. The plots are from 0° to 90°N , with dashed lines at 30° and 60°N .

Figure 4. As in Fig. 3, but at 465 K. Temperature contours run from 200 to 230 K. Layout is as in Fig. 3.

Figure 5. As in Fig. 3, but at 1700 K. Temperature contours run from 220 to 280 K. Layout is as in Fig. 3.

Figure 6. Cross-sections of sPV (10^{-4} s^{-1}) around 60°N , from UKMO (left) and USMM (right). The contour interval is $0.3 \times 10^{-4} \text{ s}^{-1}$; $1.2\text{--}1.5 \times 10^{-4} \text{ s}^{-1}$ is shaded.

Figure 7. Isosurfaces of sPV from data (left) and model (right), on 16 Dec 1998. The $1.6 \times 10^{-4} \text{ s}^{-1}$ surface is shown for the UKMO data, the $1.8 \times 10^{-4} \text{ s}^{-1}$ surface for the USMM. The vertical range is 450–1600 K.

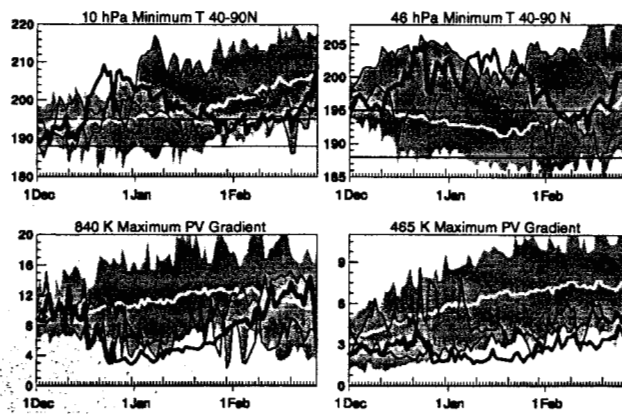


Fig. 1

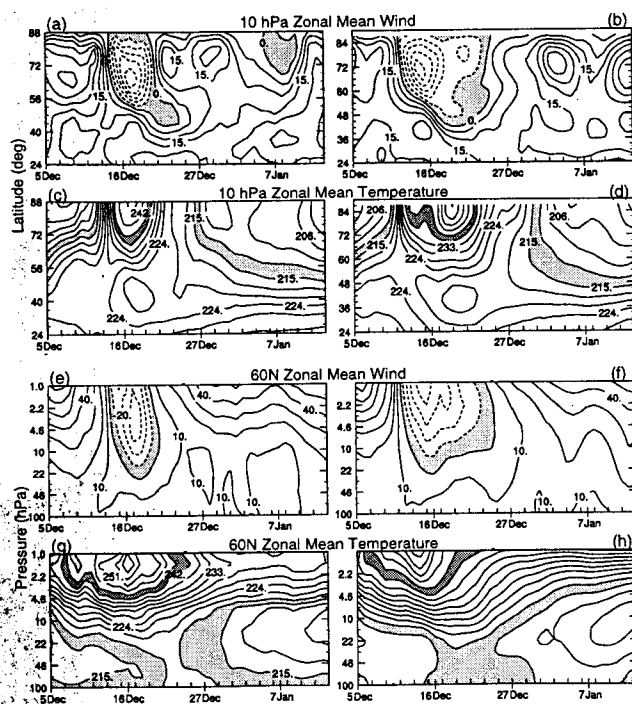


Fig. 2

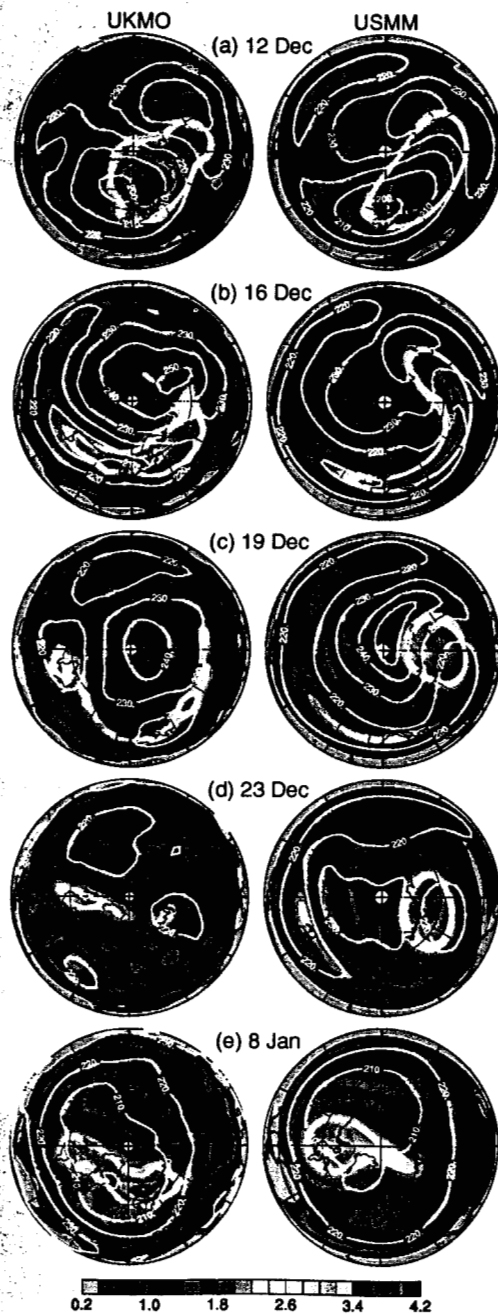


Fig. 3

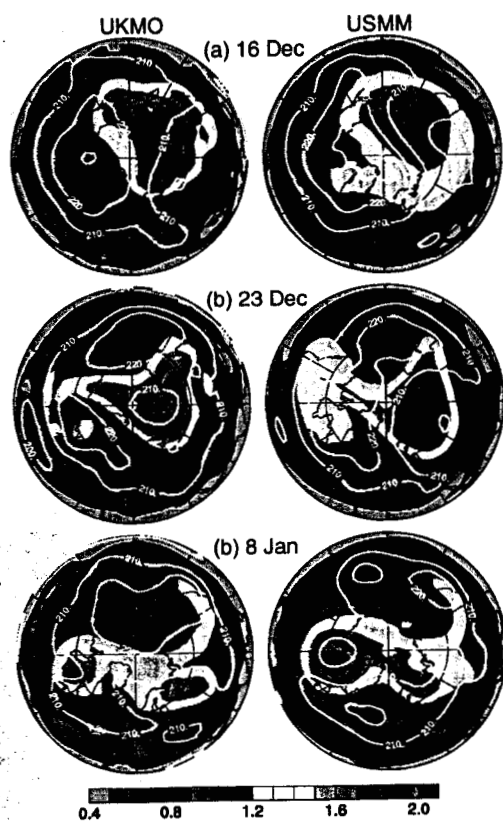


Fig. 4

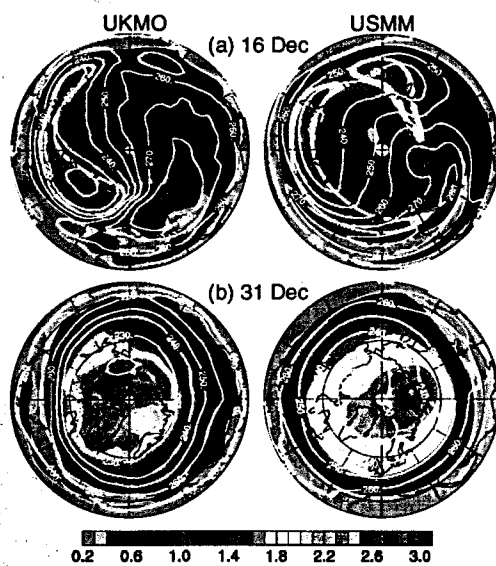


Fig. 5

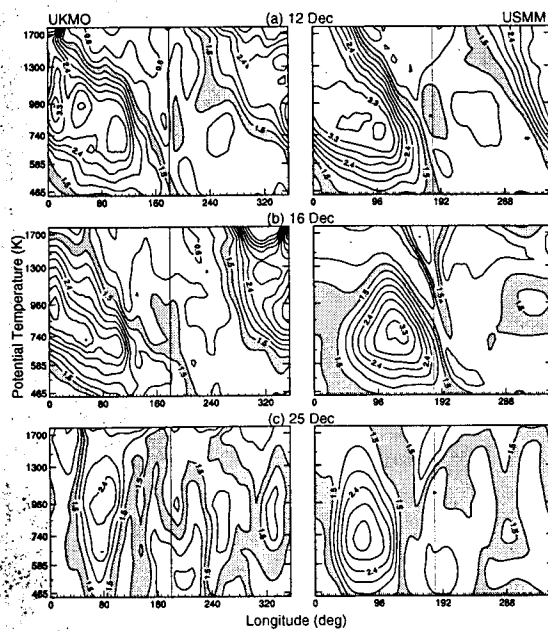


Fig. 6

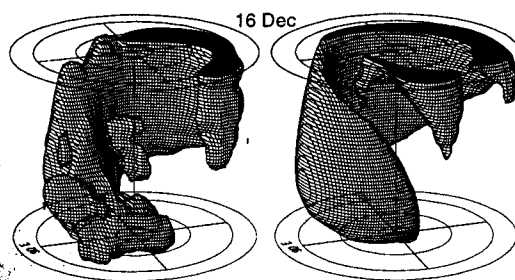


Fig. 7